5.0 GENERATION OPTIMIZATION

Every kilowatt-hour of electricity produced by a nuclear plant replaces a kilowatt-hour of electricity that would have to be produced using some other technology. At present, the only viable alternatives to nuclear for baseload power plants are coal, oil, and gas, all of which produce greenhouse gases, and varying amounts of chemical pollutants. Assuming no new nuclear plants will be built in the near term in the United States, the strongest contribution that can be made by the nuclear energy sector to minimizing greenhouse gas accumulations is to ensure that currently operating plants produce the highest energy output consistent with safe operation. The maximization of output requires that the plants be kept operational through the end of their safe, reliable, and economic lifetimes, that their performance be optimized for maximum power output and availability, and that the operating licenses be renewed to extend the plants' operating lifetimes. The highest justifiable power levels and the greatest possible capacity factors are vital.

The goals of the generation optimization element of this Plan are to address key technological issues and human performance issues that support longer plant operating lives and that support the desired improvement in operational performance. This improvement is necessary not only for increased plant output, but also to ensure the sustained economic competitiveness of all U.S. nuclear plants as the U.S. utility industry completes the transition to a deregulated environment. An additional goal within generation optimization is to transfer and apply technologies developed for advanced light water reactors (ALWRs) to meeting current plant needs. Examples of this include improved source term methodologies, improved combustible gas control systems (passive autocatalytic converters), etc.

Research and development for generation optimization are needed in the following technology areas:

1. Instrumentation and Controls (I&C)

   R&D for this area needs to address the technological and institutional and regulatory issues which impact the feasibility and cost effectiveness of replacing deteriorating, obsolete, and inefficient analog I&C systems with digital systems, particularly for safety significant systems.

2. Advanced Sensor Technologies

   R&D for this area is required to improve the accuracy, reliability, and comprehensiveness with which key process variables are measured and other plant information is obtained.

3. Advanced Monitoring, Diagnostics, and Control Systems

   R&D for this area needs to focus on the development of systems that will provide effective on-line and off-line support to plant operations, maintenance, and engineering staffs to optimize plant operation and maintenance functions.

4. Organizational Factors and Human Performance Issues

   R&D for this area needs to focus on understanding how organizational factors drive human performance. Organizational factors include all that is needed to enhance performance of the human contribution to overall plant performance, and to avoid risk caused by human error. In addition, R&D needs to address the effects on human performance of changes in plant equipment and procedures, and changes in workforce demographics.

5. Advanced Safety Analyses

   R&D for this area needs to focus on determining the transients which limit the rated power of a plant in order to develop advanced safety analyses methods which can allow increases in rated power while maintaining adequate margins for safe operation.

6. Advanced Nuclear Fuel

   R&D for this area needs to focus in the short term on improved reliability and resolution of recent licensing issues related to high burnup fuel performance. Longer term R&D should focus on achieving even higher burnup fuel cycles, using higher enrichment fuels, in order to extend the time between refueling outages consistent with limitations imposed by other parts of the nuclear plant.

7. Risk Technologies

   R&D in this area needs to focus on developing more accurate and comprehensive PRAs, which expand our knowledge of low power and shutdown risk, and the impacts of organizational factors on human reliability. Another focus is to improve and expand the uses of PRA for decision-making, such as developing a risk-informed approach to determine the effects of implementing digital technology, or to establish risk-based performance indicators.

8. Other Generic Generation Optimization R&D

There are other R&D topics that are important to generation optimization but do not fit the categories previously mentioned. One significant area is that of addressing the potential plant vulnerabilities resulting from degradation of transmission grid voltage inadequacies.

Each of these technology areas contributes to the goal of generation optimization through increases in one or more of the following subgoals:

a. To keep existing plants operating (as long as they are safe and commercially viable),

b. To get more hours of operation out of each plant per year, and

c. To get more power per hour of operation out of each plant.

The specific quantities that are most significantly improved by each technology area are indicated in Table 1.

Table 5-1: Technologies for Optimization of Nuclear Plant Power Generation

	I&C	Sensor Techno-logies	Monitoring, Diagnostics, and Control Systems	Organiza-tional Factors and Human Performance	Safety Analyses	Advanced Nuclear Fuel	Risk Techno-logies	Other
More Years of Operation/Plant	x		x	x	x		x	
More Hours of Operation/Year Per Plant	x		x	x		x	x	x
More Power/Hour of Operation	x	x	x		x	x		

A description of each technology area is provided below, along with specific work to support the objectives in the area.

5.1 Installation of Digital Instrumentation and Control (I&C) Systems

Resolution of issues surrounding the use of digital instrumentation and control systems, especially in a licensing environment, is needed for wide-scale implementation of this technology. The management of the degradation of analog instrumentation and control components in many operating plants is reaching a critical point in many countries. Most plants have obsolete components that are no longer being produced commercially and that need frequent re-calibration and maintenance. Their failure has led to about 38% of the Licensee Event Reports filed by utilities. Many plants in the United States and around the world are considering or are embarking on upgrades (modernization) utilizing digital-based systems to take advantage of a commercial base of vendors; improved resistance to calibration drift; and increased capability for self-diagnosis, data handling, and easy maintenance. In addition, deregulation and license renewal are pushing modernization of I&C systems and components to improve availability, reliability, productivity and standardization; to reduce operation and maintenance (O&M) costs; and to enhance safety. However, several outstanding issues have been identified concerning the use of digital technologies in nuclear plants. Potential issues concerning the use of digital I&C in nuclear power plants have been documented in a National Research Council report, *Digital Instrumentation and Control Systems in Nuclear Power Plants: Safety and Reliability Issues* (National Academy Press, 1997). The U.S. utility industry agrees that some of the identified issues are valid, but considers others to be not significant. In either case, because of regulatory concerns, industry must address these issues, when they replace older safety systems with new digital safety systems. Furthermore, the British, the Canadians, the

French, the Japanese, the Koreans, and the Taiwanese have also had to address issues involving the use of digital systems in new plant designs. The issues identified in the National Research Council report are described briefly in the following text.

The use of digital I&C systems may introduce new types of failure modes that can affect operations and/or safety. Modern applications of digital I&C use multi-layered architectures in which local controllers perform component-level control functions, higher-level controllers coordinate in a supervisory way the control of systems of components, and still higher-level stations perform plant-level supervisory functions and data analyses. There are performance aspects of systems that transcend the particular components that comprise the system or even the functions of the system itself. These "systems aspects" include the performance of the architecture of the I&C system, the communication between various levels of the architecture, the allocation of functions to various parts of the system, the distribution of computing resources throughout the system, the security of the system, and the ability to upgrade the system components easily while dealing with the concern that unconnected, uncoordinated systems could reduce operational efficiency and have the potential to overwhelm the operator. The issue concerning these systems aspects, particularly for backfits, is that the effects of operation of one component on another in a distributed multi-layered system are sometimes overlooked. There have been instances of "data storms" in which so much data is requested by some subsystem that the communication networks bogged down.

A second issue is the lack of a generally accepted solution to specifying, producing, and controlling the software needed in high-reliability nuclear systems. Most software QA processes involve controlling the software design process and/or testing the software produced for satisfaction of the requirements. Experience has shown that neither of these approaches has proven totally satisfactory.

A third issue is the possibility of common modes of failure in software-based systems. One way of achieving high reliability in systems is through the use of redundancy. The threat of a common mode of failure (or a common cause of failure) raises concerns about reliability claims if the redundant systems cannot be proven to be diverse. It is difficult to prove that software-based systems are diverse if they serve the same functional requirement. This is true because so many software systems use the same building blocks and basic algorithms, generally at a low level (such as square root calculations) unseen by the system designer.

A fourth issue is the difficulty in assessing the safety and reliability of digital systems. There is no accepted approach for calculating a quantifiable reliability value for a software-based system.

A fifth issue is the lack of an agreed-upon, effective methodology for designers and regulators to use in assessing the overall impact of computer-based, human-system interfaces on human performance in nuclear plants. Digital technology offers a rich environment for advisory systems, display systems, and alarm filtering. However, it is difficult at this time to predict the impact that reliance on these types of digital-based systems will have on cognitive and/or manual errors.

A sixth issue is the need for a mutually acceptable methodology for evaluation and acceptance of the use of commercial off-the-shelf (COTS) digital systems in nuclear plants. The National Research Council panel pointed out that the use of off-the-shelf technology for digital systems is a good idea if the application in the nuclear plant is very similar to that in the commercial experience base. If the application is very different, however, the fact that there have been many instances of successful usage in other applications is by no means adequate proof that the new application will be successful. EPRI, the utilities and the Nuclear Regulatory Commission (NRC) have recently agreed on a methodology for the use of COTS equipment in nuclear applications. This methodology needs to be tried in some demonstration applications.

A seventh issue examined by the NAS panel is "case-by-case licensing." The concern is that the regulatory bodies around the world will examine digital applications on a case-by-case basis, without a common set of reference points. NRC has recently issued a revised Standard Review Plan for licensing digital-based I&C which should provide stability to the process of licensing of new systems; however, there is still a concern about regulatory ratcheting, in which the number and scope of questions increases from one license application to the next.

An eighth issue is a concern about the adequacy of the technical infrastructure within the NRC and the nuclear power industry to support the use of digital I&C in safety and safety-related systems. The research program of the NRC and the industry seemed [to the NAS panel] to be disjointed, with no strategic thrusts. The panel recommended that a strategic plan be developed, drawing together the needs [and perspectives] of the major stakeholders. There is also a concern that the research supported by NRC, the industry, and DOE does not receive strong peer review by recognized experts in the human factors and the software engineering communities.

5.1.1 Current R&D

EPRI, several utilities, and the NRC have been involved in some aspects of digital systems for nuclear plants for the past few years. A guideline was developed to identify requirements for licensing digital systems that has been endorsed in a generic letter by the NRC. This guideline is being revised to reflect the revision of the 10CFR50.59 regulation. Another guideline was developed on electromagnetic compatibility and it received a safety evaluation report (SER) from the NRC. Good progress has been made in the generation of an approach for utilization of COTS equipment in nuclear plants that is acceptable to regulators and designers alike. The guideline on COTS has also received an SER. A guideline was also developed on the generic acceptance of commercially available programmable logic controllers (PLCs) for safety and safety-related systems. An SER has been received on this also. As the next phase to this effort, two commercially available PLC-based platforms have been qualified for safety applications. An SER has been issued for each of these platforms. Finally, a guideline for on-line instrument monitoring with redundant sensors supporting calibration reduction has been developed and an SER has been issued on it.

EPRI has developed strategic planning methodologies to support utilities in determining when and how to modernize I&C systems. These methodologies are used for developing Life Cycle Management Plans, Plant Communication and Computing Architecture Plans, Upgrade Evaluation Reports, and System Maintenance Plans. EPRI has also developed a number of digital system implementation guidance documents besides the ones mentioned above. These include guidelines on software verification and validation, abnormal conditions and events, and requirement definition.

The NRC has been funding some work in the development of regulatory guidelines for digital-based systems as well as some work on the environmental effects caused by high temperature, smoke, and electromagnetic pulses on digital systems. Furthermore, the NRC has collaborated with the Halden Reactor Program to investigate automated tools for evaluation of software. The Halden Reactor Project is also looking at human-system interfaces for digital systems to improve performance and reduce the likelihood of errors. In the early 1990s, NRC reviewed and approved via Safety Evaluation Report the ALWR Utility Requirements Document, prepared and submitted to NRC by EPRI in 1987-1990. Those utility requirements specified state of the art man-machine interfaces and digital-based systems for future reactor designs. These requirements were followed by the three ALWR designs developed and submitted for approval by NRC, and certified by rulemaking in 1997 (ABWR and System 80+) and 2000 (AP600).

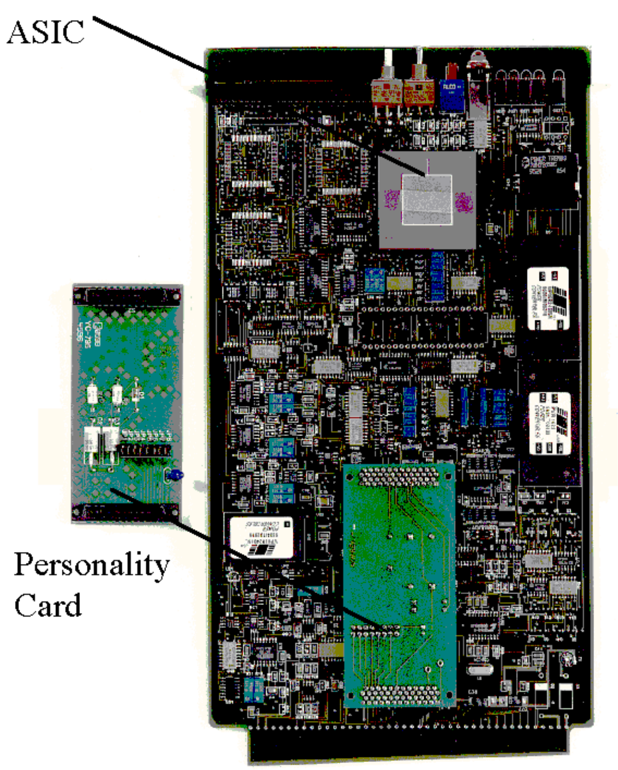

Figure 5-1: Universal ASIC modules directly replace analog cards in nuclear protection systems

EPRI, the Westinghouse Owners Group, and Westinghouse are jointly funding a program on the use of Application Specific Integrated Circuits (ASICs) for replacement of reactor protection system modules and some control modules for Westinghouse nuclear plants (see Figure 5-1), that are seeing the first ASIC-based modules implemented in 2000. EPRI is working with a number of utilities and PLC suppliers to generically qualify commercially available PLC-based systems for safety applications. SERs have been received on two of them so far. Three utilities have made the decision to modernize a majority of their control and protection systems over several outages. Operators of these three plants, Surry, Callaway, and Comanche Peak, have cited the following drivers, or benefits, for this modernization: obsolescence, productivity, license renewal, and standardization. In all three cases, one of these two generically qualified PLC-based systems has been selected for the safety systems.

An initial evaluation of a dynamic safety system approach for reactor protection systems has been completed. EPRI is completing work with a utility to design and implement a distributed plant process computer system that will support integration with distributed control systems in the future.

Under the Nuclear Energy Plant Optimization Program, the following project was initiated in FY 2000.

Project ID: 5-12

Project Title: Revision of Guideline on Licensing Digital Upgrades Based on New 10CFR50.59

Project Description: The principal objective of this project is to develop a technical basis and guidance that will clarify issues affecting application of the pending revision of the 10 CFR 50.59 regulation to digital equipment. The approach will be to revise and update EPRI TR-102348, "Guideline on Licensing Digital Upgrades," which will be rendered partially obsolete by the pending regulation revision. Activities will involve developing and documenting the technical approach, and conducting appropriate industry-wide reviews and refinements to help ensure its broad acceptance.

5.1.2 R&D Needs

For most of the issues described above, the approach recommended by the National Research Council report is for the development of a consensus on best practices for handling the issues. In addition, more research needs to be done to obtain information to better address some of these issues. To provide a focus for a dialogue among designers, owner-operators, regulators, analysts, and other stakeholders, demonstration projects at nuclear power plants are required. These projects will show best practices for addressing several issues in the design, evaluation, and licensing of digital safety and control systems. Applications using new digital-based technologies and guidelines need to be developed to prove the applicability of the new technologies and guidelines, to develop lessons-learned experience, and to demonstrate cost and benefits.

The goals of this technology area are to develop the most promising approaches for the most simple and controllable software and hardware designs for nuclear power plant safety and control systems that are also highly reliable and cost-effective. ASIC and programmable logic controllers are proven technologies possessing the benefits of digital technology without many of the perceived disadvantages associated with software. Limited function ASICs and pre-qualified PLC-based systems can substantially reduce the development and qualification costs of the system while reducing the licensing risk of implementing digital systems. By limiting the number of possible functions of the system, potential failure modes are limited; testing is also simplified and regulatory acceptance should be easier. Research in this area would develop approaches and guidelines to take advantage of proven technologies to develop cost-effective solutions.

The application of the technology resulting from work would:

- Facilitate continued long-term operation of nuclear power plants
- Facilitate the overall improvement of nuclear power plant performance

Another goal will be to develop a safety critical architecture for embedded applications using commercially available software and hardware, and obtain acceptance of the approach by the NRC. For a limited number of key safety systems, the nuclear power industry requires systems with the highest level of integrity. Static safety systems (the conventional fail-safe systems used today), although highly reliable, require periodic manual testing to demonstrate that they are maintaining their fail-safe design and will function when required. A safety critical architecture could be designed to dynamically (on-line self-checking) verify, in a continuous manner, the correct function operation of the system by comparing the inputs and outputs of the system. In addition, techniques could be developed to identify a suite of tests to assure highly comprehensive coverage with the test cases for both safety and non-safety systems.

An additional goal is to develop human factors guidance for digital systems and for hybrid control rooms. This guidance would support the design, implementation, operation, and maintenance of digital systems. It would also cover training for the operation and maintenance of these digital systems. Careful digital I&C system design and integration into control rooms can reduce human errors and inefficiencies, resulting in improved plant safety, availability, reliability, and efficiency. Conversely, human performance weaknesses may occur without proper attention to design, implementation, operation, maintenance, and training. For example, a NRC study of five events involving digital technology found human performance weaknesses in the following areas: (1) over reliance on digital instrumentation, (2) operator understanding of plant conditions, (3) human-system interface design, (4) operator training in all aspects of system operations, and (5) normal and abnormal operating procedures. The NRC staff that evaluates human factors submittals related to I&C relies on Chapters 18 and 13 of the SRP (NUREG-0800), NUREG-0711, and NUREG-0700, Rev. 1. Although these NUREGs are important, they are only intended to guide NRC review to ensure a plant meets safety requirements. They are not designed to provide guidance needed to achieve the improved human performance possible by utilizing the power and potential of modern digital I&C technology.

Finally, productivity improvements are essential for cost-effective plant operation in a deregulated environment. These can be achieved by better control systems, control algorithms, sensors, procedures, best estimate safety analyses, and calculations of uncertainty margins.

It has been suggested that to facilitate the accomplishment of the above and other goals in this plan element, generation optimization testing facilities could be used where new I&C and human factors technologies can be evaluated prior to installation in operating plants. The National Academy of Sciences report on “Digital Instrumentation and Control Systems in Nuclear Plants, Safety and Reliability Issues” recommended that DOE and NRC consider coordinating a facility in which the U.S. nuclear industry can prototype and empirically evaluate digital-based I&C and proposed designs for human-system interfaces. Such a joint facility could be used to evaluate the impact of new commercially available off-the-shelf digital-based technologies that may be proposed for plant protection, control and monitoring/diagnostics.

Specifically, the facilities would support: development testing methodology to assess and assure equipment and software quality; development and evaluation of industry standards; commercial off-the-shelf equipment evaluation; evaluation of cost effectiveness of proposed I&C replacements and upgrades; testing and evaluation of new developments such as sensors, ASICs, PLCs, and wireless technology; testing and evaluation of distributed control networks; evaluation of system diagnostic methodologies; evaluation of human performance in a complex process control environment; and evaluation of new control room designs and retrofits on operator performance.

The facilities would provide the needed testing resources for use by DOE, national laboratories, utilities, reactor owners groups, NRC, and international collaborators. These might include some of the following: Digital to Analog (D/A) and Analog to Digital (A/D) interface options for connecting hardware to plant simulations; virtual laboratory capability to provide remote utilization; communication architecture test bed to evaluate different protocols and to test "plug and play" I&C replacements such as ASICs, PLCs, etc.; sensor testing; diagnostic methodologies testing capability; environmental testing; maintenance training and strategy testing; and modular generic simulations capable of rapid reconfiguration to represent the dynamics of commercial reactor types.

The need for such facilities should be evaluated and the necessary capabilities identified. There are several facilities available that can provide pieces of the suggested capabilities discussed above.

The high priority projects identified for FY 2001 are listed below, along with a brief project description. See Volume II for detailed descriptions of these projects.

Project ID: 5-12

Project Title: Revision of Guideline on Licensing Digital Upgrades Based on New 10CFR50.59

Project Description: This is continuation of a project initiated in FY 2000. The scope of work for FY 2001 is to finalize the draft guideline document prepared in FY 2000.

Project ID: 5-110

Project Title: Human Factors Guidance for Digital I&C Systems and Hybrid Control Rooms

Project Description: The principal objective of this project is to provide human factors guidance for the design of modern digital components and systems, and hybrid control rooms in which digital units are co-located with analog units to ensure that in addition to meeting NRC safety requirements, the plant will realize significant reduced human errors and inefficiencies, resulting in improved plant safety, availability, reliability, and efficiency. This project will develop and document human factors guidance for specifying and designing digital components and systems, and their incorporation into analog and mixed analog/digital (hybrid) control rooms, remote shut-down panels, etc. The guidance is intended for application by utilities and suppliers of digital I&C replacements.

5.2 Advanced Sensor Technologies

Nuclear plants need improved sensors to more accurately measure the plant's state at reduced cost. Process sensors are at the heart of nuclear plant operations, providing information for plant protection, control, and maintenance.

Current plants are operated at less than their designed power because of uncertainties in process variable measurements. The existing sensors experience problems such as obsolescence, excessive surveillance and calibration requirements, inaccuracy and unreliability, and inability to directly measure parameters of interest. The goal of maximizing the power produced by nuclear plants thus creates a need to minimize measurement uncertainties through the development of new sensors to measure pressure, level, temperature, flow, radiation, neutron flux, coolant chemistry, hydrogen in containment, strain, displacement, velocity, and acceleration. In addition, measurement uncertainties can also be minimized for existing sensors by additional testing and by improved analytical techniques. Another area of importance to address obsolescence and reduce uncertainties is the generic qualification of commercially available sensors for safety applications.

<u>Improved pressure measurement</u>
Pressure is a fundamental process variable that requires accurate and reliable measurement throughout nuclear plants. Conventional pressure sensors have been studied extensively, yet significant areas remain for performance enhancement. Drift in pressure sensors is often 1–2% over a fuel cycle. Many conventional pressure sensors use oil to buffer the gauge mechanism from the process fluids and are subject to undetectable failures if the oil leaks. Moreover, verification and calibration of the performance of conventional pressure sensors requires significant periodic effort. The non-nuclear process control industry is undergoing a revolution in pressure measurement due to the advent of the single-chip pressure transducer. This is rapidly making the traditional pressure transmitter obsolete.

Fiber optic based pressure sensors offer a potential solution to the accuracy, calibration, reliability, and obsolescence difficulties of conventional pressure transmitters. They offer the advantages of reduced mass and size, resistance to vibration and shock, physical flexibility, high sensitivity, electrical isolation, immunity to electromagnetic interference (EMI), superior resistance to high temperature and radiation, reduced calibration requirements, and passive operation.

<u>Improved radiation measurements</u>. Reactor power is a key safety parameter at nuclear power plants and measurement of neutron flux is the accepted method for determining this power. Current flux measurement devices suffer from several limitations such as EMI sensitivity, single point of measurement, large size, cross sensitivity to gamma rays, and need for several separate systems to cover the entire flux range. Optical fiber-based radiation detectors have the potential for solving many of these limitations. A distributive method for making direct measurement of reactor power would address many of the limitations exhibited by current methods and result in

increased accuracy both in measured absolute power and in spatial power distribution, offering substantial potential for improved efficiency, increased capacity factors, and enhanced safety.

Improved primary flow loop measurement. Primary loop flow measurements are used to determine the core heat rate in PWRs and as such are a primary parameter in plant thermal efficiency. These measurements are conventionally made using flow meters based on differential pressure. A differential pressure flow meter consists of a flow-restricting orifice with pressure measurement devices located on either side. Such differential pressure flow meters have several fundamental performance limitations. Over time, contamination products can build up on the orifice, thereby changing its calibration. Also, some differential pressure transmitters have a failure mechanism (oil leak) that cannot be readily detected while they are in service. In addition, in differential pressure-based flow meters, the pressure change varies non-linearly with flow rate, thereby limiting the range of the measurement and reducing its accuracy. Improved flow measurement could be attained through improved pressure measurement (see previous discussion) and use of “on-line” linearization.

Improved feedwater flow measurements. Feedwater flow measurements play an integral role in the calculation of the thermal power output in nuclear power plants. Measurement uncertainties must be included in the calculation to assure that the thermal power output does not exceed the licensed thermal power limit. The uncertainty margin put into the thermal power calculation to cover feedwater flow measurement uncertainties reduces the power output of the plant. Accurate feedwater flow measurement instrumentation and analysis allows for more accurate assessment of plant calorimetrics and plant thermal power. Plants that can demonstrate reduced uncertainties in the feedwater flow measurement can justify reducing the uncertainty margin and increase power generation. New ultrasonic flowmeters have been developed and are commercially available. In fact, utilities are taking advantage of them to reduce uncertainty margins and increase power output. However, the actual plant uncertainty in measurement is dependent on plant-specific hydraulic conditions such as flow regime, temperature, pipe roughness, and piping configuration. Improved instrumentation, experimental testing, and analysis can address these areas of uncertainty to reduce their magnitude and help justify uncertainty margin reductions. Experimental testing at more typical plant conditions and improved analysis and understanding of the physical phenomena can support even more reductions in the uncertainty margins. In addition, orifice plates and other improved instrumentation have the potential to support even more accurate measurements of flow and calculated power output.

Improved temperature measurements. Temperature is a primary parameter in power plant thermal efficiency. Conventional temperature sensors suffer from a variety of limitations such as drift, limited accuracy, EMI and radiation sensitivity, slow response time, and need for isolation from the process fluid. Fiber optic temperature sensors have the potential for overcoming all of these limitations. Plant thermal power directly corresponds to the temperature rise of the primary coolant. A differential temperature reading that is one percent too large reduces plant thermal power production by one percent. (EPRI has reported that at one plant a one-percent temperature measurement error leads to a 3.7% decrease in turbine efficiency if the sensor reads high and loss of component life if it reads low.) Resistance thermometer and thermocouple drift of a few percent is not uncommon in normal operation. Assuming a 2¢/kW-hr price for electricity, a one-percent loss in generation for a 1000 MWe plant corresponds to a loss of $1.7 million per year. In addition to immediate operational savings, improved temperature measurement has the potential for increasing the maximum allowed plant thermal power. By decreasing the uncertainty in the measurement of peak process temperature, the margin required between maximum allowed operational conditions and equipment failure could be reduced.

5.2.1 Current R&D

EPRI has several advanced sensor R&D projects under way now for:

a. Instrumentation on-line monitoring and calibration reduction
b. Generic qualification of smart pressure transmitter for safety applications
c. Prototype ultrasonic Pressurized-Water Reactor (PWR) coolant flow/temperature measurement
d. Advanced in-core power sensor
e. Fiber optics in nuclear plants

Under the Nuclear Energy Plant Optimization Program, the following project was initiated in FY 2000.

Project ID: 5-10

Project Title: Qualification of Smart Transmitters for Nuclear Safety Applications

Project Description: The principal objective of this project is to qualify selected smart transmitters, performing the qualification testing and evaluation activities that can be done on a generic basis. This will save utilities and equipment suppliers from individually repeating the tasks for each application, and at the same time it will reduce regulatory risks to the utilities. It will also enable the utilities to approach both the equipment suppliers and the NRC as a group, conserving resources for all the parties involved. The work will involve planning, performing, and documenting evaluations and testing of a selected smart transmitter to qualify it for use in safety-related applications in nuclear power plants. In evaluating attributes such as failure modes, undesired behaviors, reliability and built-in quality of the subject device, the project will seek to address the 10 CFR 50.59 implications that could arise due to potential untoward behaviors of the transmitter.

5.2.2 R&D Needs

The purpose of this technology area is to develop and improve sensor capabilities for: (a) measuring important process parameters such as flow, fluid level, temperature, pressure, coolant chemistry, radiation, level, vibration and steam quality; (b) detecting and locating potential leaks in the steam generator as well as throughout the plant; and (c) on-line monitoring of components (valves, pumps, heat exchangers, cables, etc. It is also necessary to have the ability to measure these physical parameters in existing plants in locations where the original designs do not provide that capability. The use of small, lightweight, easy-to-install, inexpensive, reliable sensors with improved accuracy could improve many aspects of plant operation. Several technologies offer promise. These include:

a. Fiber optic sensors and data communication networks.
b. Surface acoustic wave sensors.
c. Ultrasonic sensors.
d. Micro- and millimeter-wave sensors.
e. Micro-cantilever-based sensors.
f. Wireless-based sensors for ad hoc monitoring.
g. Micro sensors for process variables.

Work needs to be done to gain regulatory acceptance of the reduction in instrument calibration proposed by the nuclear industry. The existing work on instrument monitoring and calibration has consisted of using multiple similar instruments. Work is needed to extend this through the development of techniques for the use of dissimilar instruments and to obtain regulatory acceptance of the use of these techniques. Demonstrations of the advanced instruments and of the calibration reduction techniques are needed to prove their reliability and benefits.

The availability of accurate sensors for nuclear power plants applications is essential for improved productivity and for maintaining safety. This availability can be accomplished in three steps. The first step would be to determine the sensor needs to replace obsolete measurement devices and to achieve higher levels of measurement accuracy. The second step would be to evaluate commercially available sensors to determine which ones would be capable of fulfilling the needs in a nuclear plant. With proper evaluation and acceptance testing and processes, these could be used for even safety applications. The third step would be to identify where available sensors would not satisfy the measurement needs of the plant. The primary objective in this situation would be to develop sensors that are more accurate and that make a more direct measurement of physical variables. An additional objective will be to develop sensors that support diagnostics and engineering analyses to increase capacity factor. Small wireless microsensors (see Fig 5-2) are a technology that can be placed where the plant personnel need hem at the moment will be developed and demonstrated. Some of these new sensors will have embedded intelligence and communication capability for remote monitoring.

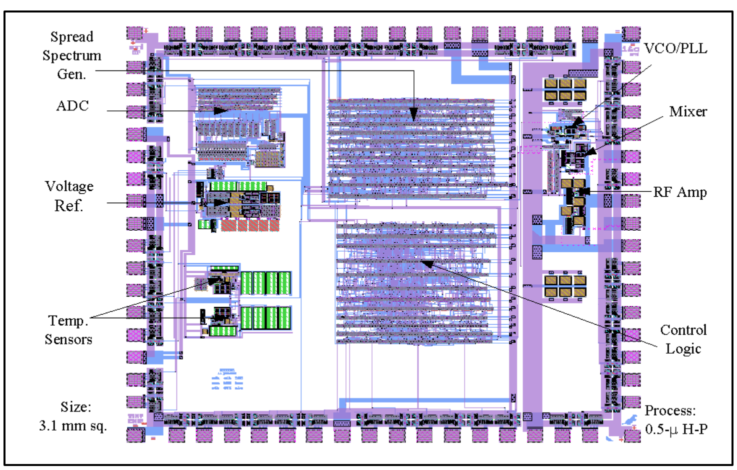

Figure 5-2: Wireless telesensor chip, Intelligent wireless sensors and systems

The high priority project identified for FY 2001 is listed below, along with a brief project description. See Volume II for a detailed description of this project.

Project ID: 5-113

Project Title: On-line Monitoring of Non-Redundant Sensors for Signal Validation and Instrument Calibration Reduction

Project Description: The principal objective of this project is to provide assistance to operating nuclear power plants in assessing, implementing and provide on-going support of MSET and other signal validation technologies and to quantify benefits of on-line monitoring. The key project tasks are:

- Perform testing of on-line monitoring technologies at power plants to establish performance, document advantages to nuclear power plants and develop cost-benefit measures with plant personnel
- Publish a EPRI report documenting the performance at nuclear power plants of MSET and other on-line monitoring methodologies
- Conduct Workshops & Training to familiarize utility users of technology

5.3 Advanced Monitoring, Diagnostics, and Control Systems

As nuclear plants age, their operations may have to be modified somewhat to account for degradation or suspected degradation of plant components such as steam generators, reactor pressure vessels (RPVs), pumps, and valves. In a complicated system like a nuclear power plant, it is impossible for humans to account in real time for the changing operational status of the thousands of components. Computerized monitoring, diagnostic, and advisory systems can offer valuable support. Operators have made limited use of such systems for many years. As computer technologies advance, the potential for improved simulation, diagnostics, and systems management increases. Furthermore, the goal of maximizing plant energy output motivates the development of vastly improved, computer-based tools for assisting operators to meet this goal. Early fault detection (before normally detected through current methods used by operators, systems engineers, and maintenance staff) will allow more time for decision making, increase the number of options for correcting the problem, reduce component damage, and support improved availability and reliability.

5.3.1 Current R&D

EPRI has supported work in this area over the past several years. This includes the development of digital feedwater control systems for BWRs and PWRs, advisory systems for the movement of fuel assemblies during a refueling outage, on-line monitoring techniques, diagnostic and maintenance guidelines, and 10CFR50.59 safety reviews. A large number of monitoring and diagnostic systems and guidelines have been developed for equipment such as piping, motors, valves, and pumps. Substantial work has been done on erosion corrosion and microbiologically induced corrosion in nuclear power plant components. Knowledge-based systems and neural network systems have been used for small prototype diagnostic systems. Improved data-handling systems have been developed to support monitoring and diagnostic systems. The Halden Reactor Project also has an active program in early fault detection, computerized operating procedures, alarm filtering, and general surveillance systems. Both EPRI and the NRC are participants in the Halden work, primarily in an advisory capacity. Several smaller projects are under way in the United States. These are mostly funded by utilities, or to some degree by the National Science Foundation. One example is a prototype on-line diagnostic system by Argonne National Laboratory working initially with Commonwealth Edison.

There are no ongoing projects under the NEPO program for this technology area.

5.3.2 R&D Needs

Despite the substantial improvements in plant operation potentially achievable with advanced monitoring and diagnostics technologies and control, there is no coordinated research program in this area in the United States. Several issues still need research and development. Among them are:

a. How can new diagnostic and advisory support systems be best exploited? This will vary from plant type to plant type, from utility to utility, and perhaps from year to year.
b. How can potential new failure modes (particularly human error) be avoided?
c. How can system reliability be demonstrated?
d. How can optimum use be made of the increased possibility for automation?
e. How effective and beneficial are the technologies in actual plant application?
f. How will the use of these systems affect plant operation and procedures?
g. How will the use of these systems affect regulatory issues?

The previous efforts in this area have demonstrated the promise and basic feasibility of a variety of computerized operations assistance technologies. A significant R&D effort is now needed to identify and integrate the most promising of these technologies, to demonstrate their reliability through test implementations in actual plants, to quantify their benefits relative to enhancement of plant energy output and operational effectiveness, and to secure the required regulatory approvals.

This technology area provides for the development and demonstration of advanced information processing technologies that allow reactor plants to be operated more efficiently and reliably, consistent with the highest standards of safety. These advanced technologies will be designed to generate and substantiate information about the condition of plant components and equipment, to use this information to justify continued or extended operation, to maximize plant energy output, and to reduce plant operating costs, particularly operation and maintenance costs. Advances in computational technologies, numerical methods, and artificial intelligence techniques will be exploited in the development of these technologies and will result in a significant enhancement of the tools available to plant operations, maintenance, and engineering staff for the performance of the following functions:

a. Processing and validation of plant signals for reliable monitoring of the plant state.
b. Analysis of process information (direct sensor readings and computed information) for accurate, dynamic determination of required and actual safety margins, with the objective of eliminating excessive conservatism that unduly constrains output with no compensating safety benefit.
c. Diagnosis of plant systems, using validated sensor readings and diagnostic test signals, for reliable characterization of component conditions as needed to optimize plant operations and maintenance and to facilitate recovery from plant upsets.
d. Management and coordination of plant operation and maintenance activities using modern information processing technologies, knowledge-based advisory systems, computerized operation and maintenance procedures, and state-of-the-art human factors expertise.
e. Advanced control and management of plant systems for optimal plant output and reliability consistent with safety criteria.
f. On-line fault detection and diagnosis to give early enough warning of sensor, equipment, and system problems to allow the staff options to potentially handle the problem before damage or a plant shutdown occurs.

Advanced process monitoring and signal validation capabilities will be developed based on new analytical techniques for plant state identification and early fault detection. These techniques provide early warning of process anomalies and/or instrument failure and in principle allow the replacement of a faulty sensor with a “virtual sensor” based on a highly reliable analytical estimate. This capability should mitigate the economic and safety penalties that can arise from sensor degradation or failure by providing the operator with timely information about the health of sensors, equipment, and systems; making it possible to terminate or avoid events that might otherwise challenge plant availability or safety goals. The process monitoring and signal validation techniques are also expected to provide a technical basis for reducing burdensome instrument calibration requirements and for scheduling corrective actions (sensor replacement or re-calibration, component adjustment or replacement, etc.) at the optimum times.

New signal validation techniques are also expected to contribute to the goal of maximizing plant output. For example, it appears possible to use these techniques to justify the operation of PWRs at higher power levels than is currently possible based on power determination using feedwater flow rate measurements. These are performed using Venturi flow meters, which are prone to fouling early during an operating cycle. This fouling causes the flow rate and thus the power to be overestimated and forces a derating of the plant. This derating can be avoided by use of the proposed sensor validation capability, which yields a reliable estimate of the actual flow rate, even after the flow meter calibration starts to deteriorate. Considerable on-line signal validation work and signal estimation work has been done, especially when there are multiple instruments measuring the same parameter. Some preliminary work has been done for on-line signal validation and signal estimation when redundant sensors do not exist. This work needs to be extended both in development of the techniques and in demonstrating the accuracy of the approaches.

Improved sensor technologies and signal validation techniques will be used in conjunction with recently developed strategies for dynamic adjustment of trip setpoints to maximize power output within the safety limits. In these dynamic strategies, the setpoints are tailored more closely to the actual reactor state than is conventionally the case (conventionally, limiting safety system settings are derived by requiring that margins to safety limits be satisfied, even when unrealistic combinations of pessimistic assumptions are employed in the safety analysis). To capitalize fully on the potential of these advanced monitoring and margin optimization technologies, software modules for optimizing estimates of the reactor state (using validated measurements and analytic models, along with their respective uncertainties) will be developed and used in conjunction with modules that dynamically adjust limiting safety system settings so that unnecessary conservatism is eliminated in demonstrating compliance with safety limits. In addition, improved analysis techniques, as well as new test data, will be used to reduce uncertainty margins to increase power output while still remaining within the safety limits.

With respect to plant diagnostics management of transient processes, there is a significant incentive to improve upon the diagnostic capabilities currently available to operations personnel for identifying the condition of plant systems and components. Enhancement of the reliability and timeliness of such diagnostic information also enhances the operators' ability to justify continued or extended operation of key components, to optimize maintenance and calibration schedules, and to take appropriate and timely actions in response to potential malfunctions. However, in spite of the interest in such advanced diagnostic techniques, their use has been limited by fundamental questions regarding the reliability of the digital software or algorithms and their underlying knowledge bases, and by the lack of portability of this software among different plant systems. To address these challenges in a fundamental manner, it is proposed to use innovative approaches in which the software's knowledge is based on fundamental physical principles and not on empirical rules regarding specific events. This allows for generic and relatively small knowledge bases, as well as for the important attribute of system and plant independence.

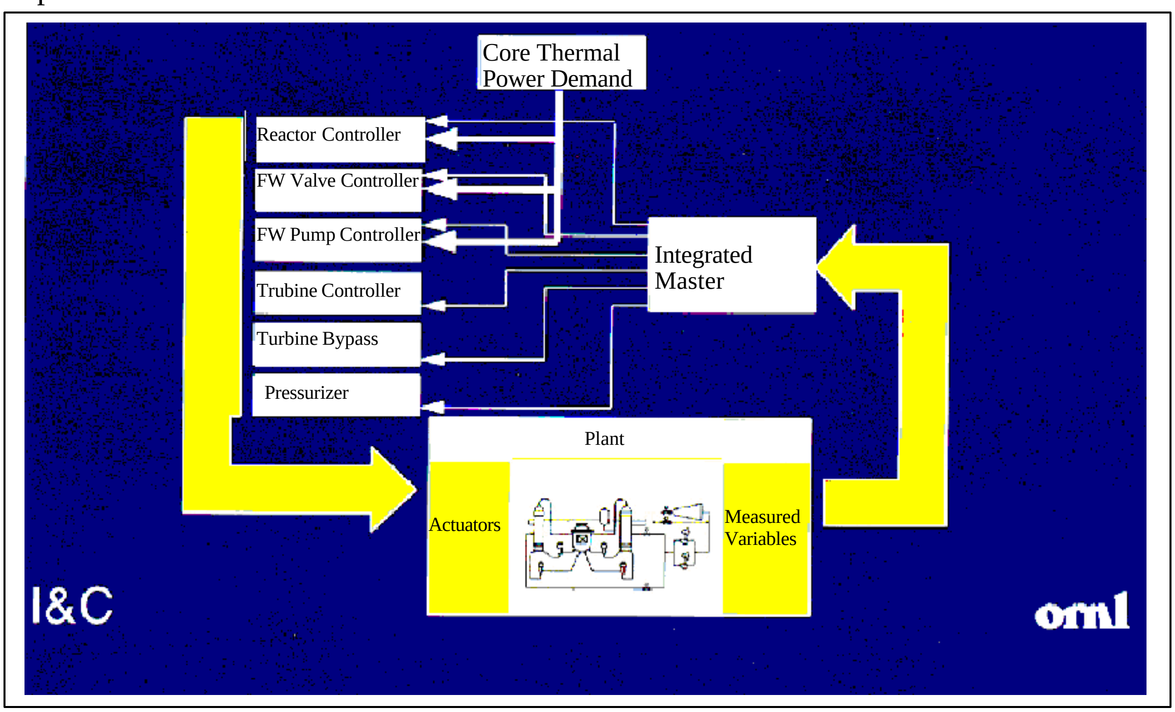

Figure 5-3: Advanced control concepts were applied to develop improved digital controllers for major systems in B&W nuclear plants

Finally, there is a strong and widely recognized incentive to develop and deploy digital simulation and control systems as a replacement for the obsolete analog controllers currently in use. Advanced digital control systems (based, for example, on optimal algorithms, neural networks, and fuzzy logic), offer the potential of economically optimum and suitably constrained control actions in response to normal or off-normal variations in the plant state (see Fig 5-3). Verification and validation of these advanced I&C systems, particularly for safety system applications, are recognized to be a key challenge.

For this technology area, no high priority projects were identified for FY 2001.

5.4 Organizational Factors and Human Performance Issues

Human performance is a crosscutting issue that affects all aspects of operational plants. Human performance includes both the human contribution to overall plant performance, and the avoidance of risk caused by human error.

The individual's role in safe operation is well understood and is being addressed, as evidenced by declining event rates over the past decade. However, the operating practices of the past are now facing challenges from new sources. Challenges to continued improvement include human factors engineering of advanced instrumentation and control systems, such as advanced monitoring, diagnostics, and digital systems. Another challenge to continued improvement at the individual worker level is changing workforce demographics. It is now widely recognized that organizational factors beyond the immediate control of individuals, such as culture, process efficiency, and communications, affect human error as well as human productivity. Indeed, these organizational factors contribute to up to 50-70 % of the problems occurring at plants. These latent problems exist in a variety of areas, including design, operations, and maintenance, and can strongly influence plant capacity as well as plant safety. Human performance issues must not be considered as adjunct to system performance issues, rather the human issues are essential components of system performance. The challenges to continued improvement in human performance need to be understood and solutions found. Tools and methods needed to enhance organizational factors, improve the performance of the human contribution to plant performance and minimize human error must be identified and developed.

5.4.1 Current R&D

The amount of research in the human factors area related to nuclear power has significantly dropped since the original impetus post TMI. However, there are a few programs specifically investigating issues such as alarm handling systems, staffing, operator aids (including a variety of advanced control systems), guidelines development for controls and displays, and automated procedures. Much of this work is being conducted in Europe, in multinational agreements among the OECD Halden Reactor Programme, the Nuclear Regulatory Commission (representing the United States as a member nation), and EPRI. One of the problems with this arrangement for the United States is that all the Halden member nations (over 15) must agree to the research program so that exactly what the US needs may not be accomplished.

More recently this research has included data development for human reliability analysis, development of automated procedure systems and alarm filtering, and methods for staffing of hybrid control stations. Work needs to continue in each of these areas. Data collection regarding human failure events needs to be continued to ensure a valid, reliable source of human factor data (better data will lead to more certain estimates regarding the relative risk of systems, and better decision making). Standard approaches to automated procedure systems and alarm filtering should also continue to be a priority such that a best industry practice evolves that will be recognized as such. Research to date concerning the allocation of tasks and staffing for hybrid control stations needs to be completed to ensure proper integration of advanced technologies into existing nuclear power plants. A major failing of all this near term work is the development of an overarching plan of how these various improvements will impact the human's performance. And as has been seen in other high risk industries, it is catastrophic to suggest that one automate the human out of the loop.

Under the Nuclear Energy Plant Optimization Program, the following project was initiated in FY 2000.

Project ID: 5-21

Project Title: Human Performance Indicators and Corrective Action Plans

Project Description: the principal objective of this project is to:

- ♦ Develop guidance on the selection and use of leading indicators to support early identification of human performance problems in maintenance, repair, and operations.
- ♦ Extend the range of utility of the analytical indicator approach and software capabilities to related issues (e.g., employee concerns)
- ♦ Develop a more comprehensive database of corrective actions taken in response to human errors at other organizations and industries.

5.4.2 R&D Needs

The R&D needs in the area of organizational factors and human performance fall into two main categories. The first category is the organizational factors affecting human performance. The second category is classical human factors engineering regarding the expected changes to control room design.

Two key research objectives in the area of organizational factors are:

<u>Description of organizational factors</u>. Building on development of leading indicators of human performance by EPRI and others, the next steps include fully describing how the various organizational factors mediate or influence the productivity and error rate of individuals. This comprehensive description can then be used to systematically evaluate the potential effectiveness of proposed management decisions intended to improve overall performance. Included in this research objective is incorporation of breakthrough knowledge

management technology to enable timely and accurate understanding of the large amounts of data needed to characterize particular organizational factors.

Description and response to changing workforce demographics. Just as plants age, the work force is aging, and will have to be replaced if plants are to operate to the extended license expiration dates anticipated. Replacement workers will come from diverse backgrounds, will be educated using different techniques, and will have other interests than workers who came before. The hands-on knowledge gained by the current generation of workers during new construction may not be readily available to future workers. Research is needed to enable leadership, management, and training techniques to be adapted to the needs of the future work force.

Four key research objectives in the area of human factors engineering are:

Impact of new technology. Determine how technology changes will affect plant availability and safety, including tradeoffs between human and hardware performance. Specific attention should be paid to the types of errors, error rates and associated uncertainty, and the quantification of their impact.

Human performance with digital control systems. Study the effects automation has on human understanding and situational awareness in regards to plant transients. Develop standards that will lead to the minimization of operational errors, recovery, operator awareness, and problem solving ability.

Development of operational philosophy consistent with life extension and advanced designs. This would include the development of a human-centered next generation control room that considers how safe is safe enough, maximizing electric power production. And, that will consider more operator monitoring, less action, changes in the timing of accidents, and new levels of staffing and organization.

Development of advanced operator interfaces. Investigate and develop advanced interfaces (virtual systems) that will improve operator awareness and understanding of plant state. These systems will eliminate concerns regarding changes in operator workload as well as situational awareness.

The high priority projects identified for FY 2001 are listed below, along with a brief project description for each. See Volume II for detailed descriptions of these projects.

Project ID: 5-108

Project Title: Organizational Factors Leadership Process Development

Project Description: the principal objective of this project to develop methods for overall improvement in plant performance through a structured process to enhance performance of human assets and to avoid risk caused by human error. A research report describing the elements of a structured approach to understanding and leading improvement in organizational factors will be produced. The report will describe key tools or process elements that enable more accurate and cost-effective measurement and control of organizational factors.

Project ID: 5-110

Project Title: Human Factors Guidance for Digital I&C Systems and Hybrid Control Rooms

Project Description: See Section 5.1.2

5.5 Advanced Safety Analysis

The rated power for an operating plant is generally limited by one of the transients, usually a loss-of-coolant accident (LOCA), analyzed in Chapter 15 of the Safety Analysis Report. The LOCA analyses were usually performed with conservative evaluation computer models as specified in Appendix K of the Code of Federal Regulations (10CFR Part 50). The conservatism of the evaluation models can lead to an unnecessarily low value for rated plant power. The Nuclear Regulatory Commission (NRC) also allows the safety analyses to be performed with best-estimate computer models as long as uncertainties in the calculations are appropriately accounted for. The use of the more advanced (best estimate plus uncertainty) safety analyses has the potential to increase the rated power while maintaining adequate margins for safe operation.

5.5.1 Current R&D

Westinghouse, together with EPRI and Consolidated Edison Co., has developed, and the NRC has approved, a methodology based on best-estimate-plus-uncertainty for analysis of large-break LOCAs. Siemens has also submitted a best-estimate-plus-uncertainty methodology for analysis of large-break LOCAs, but the methodology has not yet been approved by the NRC. Application of these methods could be used to raise the rated power of a plant that is limited by a large-break LOCA. However, a best-estimate-plus-uncertainty methodology has not been demonstrated for other transients, such as LOCAs initiated by small breaks. Westinghouse, Consolidated Edison, and EPRI are currently developing the methodology.

EPRI is refining and integrating its various core, system, and plant safety performance codes, and applying them to risk-informed analyses that support regulatory improvement. For example, EPRI is embarking on a program, in cooperation with NRC, to apply best estimate analysis and risk insights to the regulatory requirements associated with PWR rod ejection as a design basis for reactivity insertion in plant safety analysis.

EPRI is organizing an effort to develop, over the next five years, an industry Standard Nuclear Analysis Package that will support all PRA, plant reload, operational and safety analysis, severe accident evaluations, risk-informed regulation, and design basis and evolving issues for all plants and fuel types. If successful, EPRI would obtain NRC acceptance of this package for licensing and plant support. With these enhanced capabilities, utility analysts would be able to identify the conservatisms embedded in past safety assessments and to identify opportunities for O&M cost and/or regulatory improvements. The package would provide both best-estimate and licensing capability in a state-of-the-art analysis package, and would enhance the capability and range of the existing EPRI methodologies to address high burnup fuel limits, plant design changes, new fuel designs, power upgrades and other analysis needs.

There are no ongoing projects under the NEPO program for this technology area.

5.5.2 R&D Needs

Traditional safety analysis codes need to be modernized, made more capable of reducing uncertainties, and addressing areas of needed regulatory improvement. They need to become more integrated and user friendly, such that once configured for a particular plant's design and operating parameters, it can analyze the various required plant transient and accident sequences without transitioning data from one code to another.

Better understanding and perhaps even integration between industry codes and NRC codes is also needed.

The transients that limit the rated power for each operating plant need to be determined. The methodology to perform advanced safety analyses involving best estimate and uncertainty calculations needs to be developed and demonstrated for each of the limiting transients.

For this technology area, no high priority projects were identified for FY 2001.

5.6 Advanced Nuclear Fuel

Developing advanced nuclear fuel designs with higher power outputs, potentially higher enrichments, and longer life help achieve the objectives of optimized nuclear generation through less frequent refueling outages, higher capacity factors, improved economics, and ultimately greater contribution to reduced consumption of fossil fuels. High performance nuclear fuel also contributes to national objectives for reduced volumes of spent fuel. This section covers both advanced nuclear fuel development and implementation issues, but also on-site spent fuel safety, storage, and monitoring issues. It does not include spent fuel issues related to off-site storage, transportation, and ultimate disposition in a repository, which are all outside the scope of this Joint Strategic Plan.

5.6.1 Current R&D

In recent years, utilities have adopted more aggressive core designs and operating strategies to improve fuel cycle economics. These practices have resulted in new operating environments and reduced operating margins. Despite the best efforts of the fuel vendors to improve their products and the plant operators to protect the fuel by improved operation, fuel-related problems (such as incomplete control rod insertion, axial offset anomalies, and failed fuel degradation) continue. Some of these fuel-related problems have appeared as surprises, i.e., new and unanticipated problems associated with new designs, which are intended to offer economic benefits and better performance.

In addition to the fuel-related problems and reduced margins, new regulatory issues have been raised about fuel of current design, *i.e.*, the behavior of high burnup fuel under reactivity-initiated accident (RIA) and loss-of-coolant accident (LOCA) situations. Although EPRI has been effective in providing analyses for use by the industry before the NRC on these issues, some operational restrictions are very likely in the near future. The industry needs a sound technology base to prevent undue and needlessly costly regulations and operational restrictions, while assuring safe operations. DOE has a direct interest in supporting the resolution of these issues.

EPRI's Robust Fuel Program has been addressing these needs since 1997. It provides a means to avoid or mitigate any adverse impact on plant operations from fuel-related problems or from NRC restrictions due to fuel issues.

This Program is addressing both current and anticipated future fuel-related issues. The issues being addressed are:

(1) lack of consistent and comparable data for fuel performance and materials behavior,
(2) corrosion/hydriding of fuel cladding and assembly hardware,
(3) crud deposition and water chemistry issues
(4) licensing concerns and uncertainties,
(5) lack of high burnup materials and fuel performance data supporting current fuel designs
(6) incomplete control rod insertion [PWR],
(7) failed fuel degradation [mainly BWR],
(8) PCI failures in Zr-liner fuel [BWR],
(9) fuel rod failure-root cause investigations
(10) new fuel designs and materials,
(11) fuel reliability versus economic benefit, and
(12) high energy cores of mixed fuel designs

EPRI arranged for a direct comparison of new materials from various vendors in a single lead test assembly with post-irradiation evaluations (PIE) using uniform test methods and reporting, providing data that is directly comparable and unencumbered by commercial bias. All aspects of fuel issues are being addressed, including materials technology, water chemistry, thermal hydraulics and neutronics.

EPRI's Robust Fuel Program is guided by the utilities, and involves active participation of fuel vendors. . Both INPO and NEI have liaison roles. This Program is coordinated with other key fuel technology work world-wide, and specifically has been developed and coordinated with DOE, since advanced fuel work is being sponsored under NERI and is part of DOE and NERAC's long term R&D Plan. The program is also being coordinated with NRC. EPRI acts in an advisory role for NRC and DOE programs to minimize the potential for duplication. The same is true for work in Europe (EdF, Halden, etc.) and Asia; EPRI is either a participant or has exchange agreements.

Under the Nuclear Energy Plant Optimization Program, the following projects were initiated in FY 2000.

Project ID: 5-17

Project Title: Cost-Benefit Study for Optimum Fuel Burnup and Cycle Length.

Project Description: The purpose of this project is to conduct the analysis to support the business case for going to higher burnup fuel, including quantification of the many costs, risks, and benefits associated with longer fuel cycles. The principal objective of this study is to identify and determine the basis, including cost and benefits, of optimum fuel burnup and cycle length for commercial nuclear power plants (BWR and PWR). Under the sponsorship of the EPRI Robust Fuel Program (RFP), a study has been conducted by the Duke Power Company to identify the optimum burnup for a Babcock & Wilcox (B&W) and a Westinghouse (W) plant based on current W and Framatome Cogema Fuel (FCF) fuel designs. The study determined that significant fuel cycle cost savings can be achieved, but that the extent of savings will be dependent on plant type and on the operating scenario. This project will extend the above work to include BWRs, as well as other types of PWRs and different types of fuels and utility operating scenarios to evaluate the cost of implementing optimum burnups on an industry-wide basis. This task will consist of two phases: Phase I was initiated in FY 00. This phase will identify the optimum burnup levels consistent with the current 5% enrichment limit (regardless of the current licensed burnup limit of 62 GWD/T).

Project ID: 5-19

Title: Impact of Nickel Oxide Solubility on Axial Offset Anomaly in PWRs

Project Description: Axial Offset Anomaly (AOA) continues to hold down core design thermal duty, costing the industry as much as $3,000K per unit each fuel reload in additional assemblies, higher enrichments, and/or more burnable absorbers. The principal objective of this project is to rapidly develop the database on Nickel solubility from NiO up to clad temperatures. These data are essential to understanding and managing corrosion product transport and deposition in the potential AOA core. Ultimately, solubility screening tools should be coupled to core design thermal hydraulic and neutronic codes to produce high duty cores with reduced AOA risk.

5.6.2 R&D Needs

As stated in Section 5.6.1, EPRI through the Robust Fuel Program is addressing the critical current and anticipated near-term future fuel-related issues. Additional R&D is needed to expedite the resolution of these issues and to cope with the many challenges associated with increasing the allowed enrichment levels throughout the industry. This implicitly includes changing the license limits for fuel fabrication, storage, transportation, and individual reactors. DOE participation in the area of advanced nuclear fuel would complement EPRI's role in addressing these issues by making available the expertise and unique facilities at DOE national laboratories.

One of the licensing limits has emerged as a critical issue for on-site storage of spent fuel, since dry storage casks are not licensed to accept the medium burnup fuel designs currently being used in plants. They are only licensed for the older, lower burnup fuel designs of the 1980s. They can accept older spent fuel from spent fuel pools, but industry will soon face situations where spent fuel being discharged from reactors cannot be moved from pool to dry storage because of licensing limitations. This will start occurring for PWRs in 2001 and for just a few years later for BWRs. Presently, the NRC's Standard Review Plan does not address dry storage of spent fuel having burnups in excess of 45 GWd/MTU. R&D is needed to provide the data necessary for licensing storage casks capable of handling today's fuel. NRC's Office of Research has expressed a strong desire to work with DOE and industry on addressing this issue.

The high priority project identified for FY 2001 is listed below, along with a brief project description. See Volume II for a detailed description of this project.

Project ID: 5-103

Project Title: Dry Storage of Spent Fuel with Burnup in Excess of 45 GWd/MTU

Project Description: The principal objective of this project is to generate experimentally benchmarked heat transfer correlations and cladding mechanical properties data that will permit or confirm practical and efficient storage (and later transportation) for spent high burnup fuel. This project consists of two tasks. In the first task, experimental and numerical investigations of natural convection heat transfer for a vertical spent-fuel assembly in an environment typical of spent-fuel storage system will be performed. The work will provide heat transfer benchmark for allowing regulatory credit for natural convection in a dry cask designed for maximizing removal of decay heat generated by high-burnup fuel assemblies. In the second task well characterized, high burnup spent fuel assemblies will be loaded and stored in a dual-purpose (storage and transportation) system designed for high burnup fuel. Cladding temperatures during the initial period of storage will be measured for three types of atmosphere (vacuum; helium; and nitrogen). Fuel integrity will be monitored over period of five years. After a sufficiently long period of storage (presently 5 years), selected fuel components will be retrieved and non-destructively as well as destructively examined. Data from Task 2 will provide confirmatory data for the storage of spent fuel with increasing discharge burnup.

5.7 Risk Technologies

The development of risk technologies has been an evolutionary process: starting with the assessment of the risk associated with design basis accidents and evolving to today's use of risk technologies for on-line decisions. Early risk studies assessed the probabilities of failures at full power and the associated consequences using full scale level one, two and three probabilistic risk assessments (PRAs) to make decisions regarding plant design and operations. Today, computerized plant risk models make it possible to assess the risk impact of changes in the reliability of equipment and personnel very quickly and accurately.

The issues in the risk technology area are related to continuing to improve and expand the uses and applications of PRA. These issues are discussed below:

Developing More Accurate and Comprehensive PRAs: Efforts continue to be undertaken to expand and improve PRA models. One example is the risk associated with low power and shutdown operations (LPSD). Past experience has shown that there is an increase in calculated reactor core damage frequency from postulated accidents initiated during LPSD operations. Another example is improved modeling of human performance in PRAs. Cognitive human errors are not well modeled and the effects of digital equipment on human performance are not well understood. A third example is the consideration of external events, such as seismic and fire, on plant risk.

Improving and Expanding the Uses of PRA for Decision-Making: The utilities and NRC make use of PRAs to determine allocation of resources, such as frequency of maintenance or assignment of NRC inspection activities. Risk 'monitors' and other methods are used to determine which equipment can be safely taken out of service while maintaining reliability above an acceptable level. The NRC's Risk Informed Oversight Program employs a hierarchical regulatory oversight framework which uses a combination of performance indicators and risk-informed inspections.

5.7.1 Current R&D

The NRC is improving its regulatory process by making greater use of methods and results of PRAs. The NRC has undertaken an effort to ensure that its policy to expand the use of PRA is implemented in a clear and consistent manner. As part of this effort, several studies were performed to evaluate the functional reliability of risk-important safety systems in commercial nuclear power plants. The methods used were to: (1) obtain system unreliability estimates based on operating experience data and compare these estimates with those used in PRAs, and (2) review the operational data to determine trends and patterns. Another result of this new NRC policy is a revised reactor oversight process to make greater use of objective performance indicators.

U.S. utilities evaluate and control low power and shutdown risk (LPSD) risk by using procedures based on qualitative guidance in NUMARC 91-06. However, LPSD studies continue with the objective of understanding the risk associated with accidents during LPSD conditions. Plants have developed and applied methods for better managing plant safety during LPSD operations. The American Nuclear Society has initiated work to develop standards for qualitative and quantitative methods for assessing LPSD risk. The NRC has issued generic letters and information notices and performed supporting risk studies with respect to LPSD conditions. The American Society of Mechanical Engineers is developing a standard for Full Power Operations.

There are no ongoing projects under the NEPO program for this technology area.

5.7.2 R&D Needs

Digital equipment and systems are being used to replace analog equipment in nuclear power plants to address the issue of obsolescence. In NUREG 0800, the NRC has presented the position that instrumentation and control (I&C) systems are vulnerable to common mode failure caused by software error, which defeats the redundancy achieved previously by hardware architecture. This position requires a plant specific Diversity and Defense-In-Depth Assessment to be performed when upgrading safety systems with digital based I&C. Addressing this concern in a deterministic manner, as has been done traditionally, can be very costly. This is especially true if a large number of digital systems are going to be implemented over time. A risk-informed approach could offer significant reduction in effort to satisfy adequate diversity and defense-in-depth when implementing a digital system.

All U.S. utilities evaluate and control LPSD risk, to some degree, by using procedures based on qualitative guidance given in NUMARC 91-06. Under these qualitative methods, risk is considered to be acceptable if specified key safety functions are controlled within specified limits. However, NUMARC 91-06 based methods provide no means to assess the level of risk either due to the reliability of the controls of any particular safety function, or comparatively between safety functions, or to provide an integrated assessment across safety functions. What is needed is benchmarking of existing quantitative LPSD PRA results to determine the correlation between configuration controls on plant operating states and the risk produced by them.

The NRC’s risk informed regulatory process is drawing increased attention to PRA techniques. Furthermore, it is recognized that current PRA s do not accurately model the effects of human performance. Traditional PRAs do not explicitly examine the contribution to human error rates from organizational factors. Instead, they implicitly include organizational factors in such ways as plant-specific equipment failure rates, or through operator hesitancy to take action. This suggests that human reliability analysis techniques could benefit from the incorporation of organizational factors as a way to uncover and reduce human errors.

The NRC’s new oversight process uses a hierarchical framework where performance affecting ‘cornerstones of safety’ is monitored through a combination of performance indicators and risk-informed inspections. The majority of the performance indicators and associated thresholds are count driven and have limited direct relationship with risk. It would be helpful to have risk-based performance indicators (RBPIs) to provide objective measures for use in assessing reactor operational performance in the context of public risk. RBPIs would include performance metrics such as frequency, reliability, availability and probability. They would provide complementary and more comprehensive risk information than the current process indicators.

The high priority projects identified for commencement in FY 2001 are listed below, along with a brief description for each project. See Volume II for detailed description of these projects.

Project ID: 5-106

Project Title: Low Power and Shutdown Probabilistic Risk Assessment (PRA) Benchmarking

Project Description: The principal objective of this project is to benchmark existing quantitative LPSD PRA results to determine the correlation between configuration controls on Plant Operating States (POSs) and the risk level produced by them. It is expected that this benchmarking will provide bounding levels of risk associated with each POS if defined configuration controls are applied. These bounding values can then be used to represent the risk level of these POSs, thus eliminating the need for further quantitative PRA assessment. The benchmark project will involve the following tasks:

- Define a set of quantitative LPSD PRA results.
- Survey existing quantitative LPSD PRAs.
- Determine correlations.
- Determine sets of specified configuration controls.
- Document results.

Project ID: 5-107

Project Title: Develop Methods to Incorporate Organizational Factors into Risk Analyses

Project Description: the principal objective of this project is to increase nuclear plant safety and improve human error modeling techniques, by:

- Developing guidelines for incorporating organizational factors into the HRA framework, and
- Developing the models needed to quantify the organizational aspects of human error probabilities.

This project will draw upon prior EPRI technology (e.g., SHARPER which provide a structured approach for incorporating HRAs into PRAs), the ASME PRA Standard, NRC and international research on organizational factors. The EPRI framework will be upgraded to include organizational influences by providing triggers where consideration of organizational factors would be warranted. The triggers and quantification models will be derived from operating experience reports, plant self-assessment and corrective action programs, and from data derived from trial application of the human performance metrics at the nuclear plants.

5.8 Other Generic Generation Optimization R&D

This area is intentionally left broad to allow for significant projects that do not easily fit into the other seven areas. There is only one project that has been identified in this area for commencement in FY 2001. It is identified below, along with a brief project description. See Volume II for a detailed description of this project.

Project ID: 5-117

Project Title: R&D Needs to Address Potential Nuclear Plant Vulnerabilities Arising from Transmission Grid Voltage Inadequacies

Project Description: The principal objective of this project is to increase nuclear plant safety and protect the transmission grid from further instabilities caused when nuclear unit might be forced off line due to grid voltage problems, by:

- Developing a risk monitor tool to assist transmission system managers in making difficult decisions involving low reserve margins, shortage of transmission facilities and technical problems in transmitting power over long lines.
- Providing ›return to service= priorities to restore system margin or determining which assets to protect to prevent erosion of system margin.

The Transmission System Risk Monitor will use existing computer grid security interface modules to provide the user interface to risk assessment capability in the EPRI Security Applications. The results will be presented on global/local basis with the ability to drill down to specific transmission zones. Maps and graphs will be used to help users to quickly identify bottlenecks in the system. The system will be able to analyze multiple transfer scenarios, for multiple seasonal load cases. The system will also have the ability to query the security applications to prioritize return-to-service options (both at the nuclear plant and on the grid), and identify equipment most critical to maintaining current system margins. The project will be conducted in two phases. The first phase will document interfaces to the system, develop display concepts, and create a functional specification. The second phase will develop the system prototype, and develop a pilot application to be demonstrated at a nuclear unit in a region of the country experiencing grid congestion.